Visual-Vestibular Motion Cueing Assessment in Maritime Rotorcraft Flight Simulators

Wajih A Memon*, Ieuan Owen and Mark D White
*wajih.ahmed.memon@liverpool.ac.uk

School of Engineering
University of Liverpool
Liverpool, UK.

There are several factors that increase the difficulty of operating helicopters to and from naval ships, such as the combination of a confined ship deck landing space, together with irregular ship motion, sea spray and unsteady airflow over and around the ship's deck and superstructure. Together, these elements form the Helicopter Ship Dynamic Interface (HSDI) environment and can produce a high risk and operational demand on the helicopter, ship and crew. [1]. To determine the safe operating limits for helicopters a safety envelope is constructed through First of Class Flight Trials (FOCFTs), to determine Ship Helicopter Operating Limits (SHOLs); the SHOL details the safe conditions for launch and recovery operations [2].

Modelling and Simulation (M&S) tools have been developed and utilised in flight simulators to better understand the complex interaction between the helicopter and the ship within the HSDI environment prior to the FOCFTs [3-6]. However, flight simulators, despite their utility, still possess limitations such as the fidelity of motion and visual cues, flight models and the integration of the unsteady ship airwake into the flight control loop. Attempts have been made to assess the fidelity of the rotorcraft simulators [5], however, a standardised guideline to assess and optimise the overall simulation fidelity is a challenge which is yet to be fully addressed [7]. The research presented in this paper is part of a project being carried out at the University of Liverpool, funded by QinetiQ and Dstl, which is undertaking a structured examination of the M&S elements of the HSDI simulation environment, Figure 1, with the aim of developing a new robust simulation fidelity matrix to support at sea flight trials.

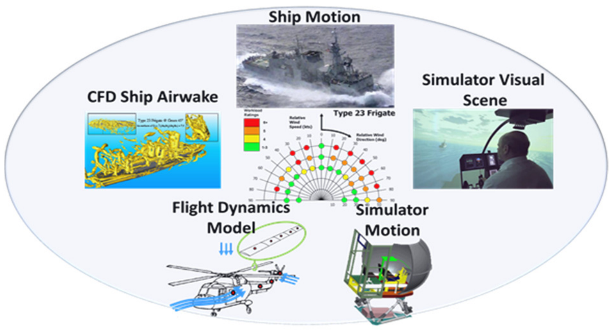

Figure 1: HSDI Modelling and Simulation Elements

Previous research has been undertaken by the authors to examine the fidelity requirements of the vestibular motion cueing in maritime rotorcraft flight simulators [8]. Results were reported of the vestibular motion fidelity research to optimise motion drive laws for simulated landing operations in presence of different ship airwake and ship motion conditions.

A variety of studies relating to simulator visual-vestibular motion cueing effectiveness have been presented in the literature. Bos, et al. [9] investigated the visual-vestibular interactions in civil/military simulators to predict human motion perceptions. Pool, et al. [10] studied the effects of peripheral visual and physical cues in compensatory tasks using their SIMONA Simulator, whilst Peterse, et al. [11] conducted a study to measure the interaction effects of different vestibular cues with and without visual cues in a land-based task. However, these studies were focused upon land-based tasks and/or fixed wing applications, and therefore new work is required to understand the visual-vestibular fidelity requirements in the complex HSDI task. Wang, et al. [12] examined the effects of degrading visual environments with and without vestibular motion cues on shipborne task performance, whilst Hodge [13] conducted an experiment to investigate visual cueing requirements in the HSDI environment using various visual scenarios at a constant vestibular motion configuration. In both of these studies, only effects of different visual cues were investigated; however, it has been found in the initial phase of the proposed research in [8] that the vestibular motion fidelity introduces differences in overall HSDI simulation fidelity and therefore the impact of variations in both will be analysed in the new research to establish overall simulation motion fidelity requirements.

The proposed paper is a new extension of the previous work, examining the coherence and interactions between visual-vestibular motion cueing fidelity in various HSDI conditions in a full-motion simulator, HELIFLIGHT-R [7]. The effects of the variation in the visual and vestibular cues on the simulation perception, task performance and pilot workload will be detailed. The different vestibular and visual motion cues to be examined have been systematically modelled for specific deck landing tasks.

Motion cues in the simulators are perceived from visual information projected onto the human eye (i.e. Vection) and from a simulator's movement detected by the vestibular system in the human ear (i.e. vestibular cues) and proprioceptive cueing [14]. The vection depends on the fidelity of the visual cues (i.e. scene content, resolution, field of view, and texture) which help the pilot to perceive their position/orientation in relation to the outside world, whilst the inertial motion of the simulator is produced by a Motion Drive Algorithm (MDA) [15], which can be tuned based on the specification of MDA washout filters. Both cues play an important role in contributing to the overall perceptual fidelity of the flight simulator, especially in HSDI tasks where the pilot requires feedback of the external factors for successful task performance [8, 12]. Poor synchronisation of the optical flow and/or inertial motion response can result in inaccurate visual and/or vestibular motion cues, leading to imbalanced self-motion perception and task performance [16].

Figure 2 shows the response of the visual and vestibular motion perception systems to the angular velocity stimulus. It can be seen that the visual system exhibits a low-pass response and, when suddenly exposed to a rotating scene without vestibular cues, a pilot may initially misperceive their position as stationary and the visual scene to be rotating [13, 17]. The vestibular system, on the other hand, responds promptly to the motion onset, exhibiting high-pass characteristics. In the real world, visual-vestibular information is normally harmonised and together form a coherent perception of motion.

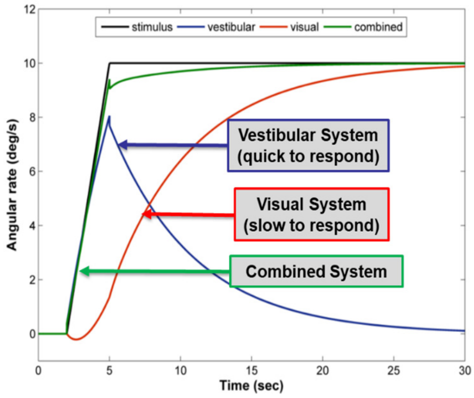

Figure 2: Motion Perception System Response to Angular Velocity Stimulus [13]

The necessity for harmonised visual-vestibular perception to accomplish a high workload task (e.g. deck landings) was demonstrated in the initial phase of this research [8]. Here an objective technique known as Vestibular Motion Perception Error (VMPE) was proposed by the authors and was utilised to optimise the vestibular motion cueing for an SH60 FLIGHTLAB model landing on two different Royal Navy ships in the HELIFLIGHT-R simulator. VMPE uses vestibular motion perception models to quantify the difference, or "error", between the vestibular motion perceived by the pilot in the simulator and in the simulated aircraft; this difference is minimised to optimise the vestibular motion cueing via tuning the parameters (k and ω_n) of the washout filters. Using this technique four different motion tuning sets (MTS) of the MDA (Benign, Intermediate, Responsive and Optimised) were derived offline for the landings on a single-spot frigate at six different WOD conditions (Headwinds: 25, 35 and 45kts, and oblique Green 45 winds: 15, 25, and 35kts). The 'Benign', as its name suggests, was predicted to provide the worst vestibular motion cues and 'Optimised' the best.

Subsequently, a piloted simulation trial experiment was conducted by an ex-RN pilot in the HELIFLIGHT-R simulator to examine the VMPE predictions. It was demonstrated by the pilot subjective assessments that at low wind speeds (i.e. 25kts) the motion perceived from the visual cues were sufficient for the pilot to perform the task since there were benign external airwake disturbances. For first three MTSs, the pilot commented: "Balanced look at visual cues" and "Satisfactory task performance". However, using the Optimised MTS case, the pilot commented: "More harmonized motion cues with visual". This suggested that using the Optimised MTS the overall motion perception improved because the vestibular motion complemented the visual cues. When the WOD was increased to 35kts and 45kts, using the Benign MTS the motion fidelity decreased to Low and pilot workload increased because the visual motion cues alone were not sufficient anymore for the pilot to accurately judge the movement and therefore perform the task satisfactorily. The pilot commented: "Poor visual-vestibular synchronisation". Whereas the motion fidelity increased to High using the Optimised MTS, where the vestibular motion complemented the visual cues. Here the pilot commented: "Could see and feel disturbances now".

In the initial motion assessment research [8], only variation in the vestibular cueing was undertaken, while the visual fidelity remained constant. In the proposed paper, three different visual scenarios of the single spot naval frigate have been modelled (high, medium and low detail), progressively reducing the textures on the ship model and degrading the visual environment (i.e. visibility) (Figure 3).

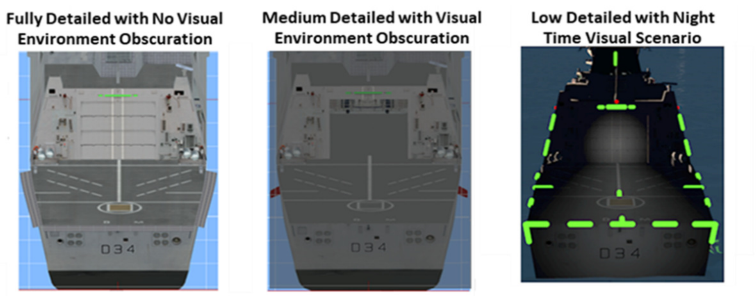

Figure 3: Three Visual Cueing Scenarios for the Flight Trial Experiment

In the high fidelity scenario, a fully detailed model of the ship is used, which includes all the deck markings (line-up line, fore/aft line, diagonal lines, deck spot and harpoon), deck perimeter netting, stabilised horizon bar, closed hangar door showing vertical lines used by the pilot extensively in hover and touchdown tasks [13] and with a clear natural horizon.

In the medium fidelity scenario, the visibility range is reduced, resulting in obscuration of the natural horizon cues which reduces the information available on the relative attitude of the ship, making it difficult for the pilot to distinguish the relative attitude of the aircraft with the horizon. This degraded visual environment will result in lack of a horizon bar reference and visual reference to the deck fore/aft line. The hangar door is open now so the pilot cannot take reference from the vertical lines for lateral positioning corrections.

Finally, a night time scenario is modelled in which the textures and details on the ship are the same as the high-fidelity scenario. Electro-luminescent Panels (ELPs) are placed onto the ship along with the floodlighting on the hangar door and deck landing spot. The ELPs are highlighting the deck markings and, along with the superstructure outline, provide ship motion cues to the pilot.

In the proposed paper the results from a new simulation trial using a range of MTSs operating in different visual cueing scenarios and WOD conditions will be reported. Variations of the visual and vestibular cues will be used to assess the effects of both visual and vestibular fidelity. The paper will discuss the impact of visual-vestibular cues, ship motion and unsteady ship airwake on overall motion cueing perception and its effects on task performance and pilot workload.

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